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Journal of Volcanology and Geothermal Research 105 (2001) 107–119

Journal of volcanology and geothermal research

www.elsevier.nl/locate/jvolgeores

Offshore continuation of volcanic rift zones, El Hierro, Canary Islands

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Received 22 March 2000; revised 9 June 2000; accepted 9 June 2000

Abstract

El Hierro is the youngest and most southwesterly of the seven Canary islands. The established view, based on subaerial geology, is that El Hierro is a classic example of an oceanic island with 120° — spaced volcanic rift arms (VRZs) forming a "mercedes star". However, new offshore data do not support this simple interpretation. Instead of the discrete ridges of VRZs, we observe (to the NW and NE) broad areas of irregular morphology, which suggest that rifting activity might not be confined to narrow zones. Furthermore, our data suggest that the anomalously long and steep-flanked Southern Ridge could be part of an older, eroded volcanic edifice that predates much of the other submarine flanks of El Hierro. The Southern Ridge has a distinctive gullied morphology, which strongly contrasts with adjacent flanks. There is also a ~400-m-deep saddle in its longitudinal profile 15 km from the coastline, which we interpret as evidence that the Southern Ridge did not form by continuous dyke intrusion from the El Hierro volcanic centre. South of the saddle, mean flank slopes are 10° steeper (~30°) with a sharp slope break at 3700 m between the ridge and smoothly sedimented seafloor. These steeper slopes and lack of landslide scars to the south of the saddle indicate that the Southern Ridge is a stable edifice, relative to the rest of El Hierro. Surrounding sediments to the southeast appear to onlap the Southern Ridge. A large landslide deposit, El Julan (estimated age >200 ka), occurs to the west of the ridge. This landslide appears to have been constrained from spreading southeastwards by the Southern Ridge, resulting in an elevation difference of 300 m for the seafloor on either side of the ridge. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Canary Islands; El Hierro; flank rift zones; Southern Ridge

1. Introduction

Many oceanic seamounts or islands have a characteristic "stellate" geometry, which tends to become more pronounced throughout the life of the edifice (Fiske and Jackson, 1972; Vogt and Smoot, 1984; Carracedo, 1994; Mitchell 1998). The main process by which these geometries are achieved is thought to be the concentration of volcanic activity along radiating rifts. Flank collapse, or slumping between volcanic rift zones (VRZs), creates embayments and enhances the general "stellate" geometry.

Based on observations in Hawaii, Macdonald (1949) was one of the early authors to suggest that oceanic islands develop along rift zones that are fed from central vents. Fiske and Jackson (1972) made a

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PII: S0377-0273(00)00241-9

detailed study of Hawaiian rifts and concluded that each island consisted of a number of single-, double- and triple-armed rift systems. Each rift arm was associated with the injection of numerous dykes which resulted in volcanic extrusions at the surface and the building of a linear ridge, extending as much as 100 km or more from the volcano summit. Emplacement of dyke material may be accompanied by magmatic and pore fluid pressurisation (Elsworth and Voight, 1995), which might result in major flank instability.

In the Canary Islands, Fuster et al. (1993) and Carracedo (1996, 1998) cited El Hierro as a classic case of a triple-armed rift system, which developed according to a geometry of least stress fracture due to updoming magma. Three well-defined ridges arranged at approximately 120° dominate the subaerial morphology of El Hierro.

The major destructive process operating on oceanic islands and seamounts is giant landsliding (Lipman et al., 1988; Moore et al., 1989, 1994; Watts and Masson, 1995; Labazuy, 1996; Masson, 1996; Ollier et al., 1998; Urgeles et al., 1999). This results in the mass wasting of hundreds or thousands of cubic kilometres of debris from the constructional flanks to form a volcaniclastic apron, which may have a volume in excess of that of the remaining subaerial edifice. Landsliding results in giant erosional embayments in the upper island flanks, which have substantially lower slope angles compared with unfailed flanks. The growth of flank rift zones may be a major factor in the destabilisation of inter-rift flank regions (Moore et al., 1989; Delaney et al., 1990; Elsworth and Voight, 1995). Moore et al. (1989) made the observation that a large number of landslides on the Hawaiian Ridge had moved perpendicular to the primary rift zones of their host volcanoes. This indicates that focussed growth along a number of radiating rift zones controls the location of landslides (Carracedo, 1994) and the means by which volcanoes evolve from simple to more irregular stellate forms in maturity (Mitchell, 1998).

There is an apparent contrast between offshore broad rift zones and onshore rift zones. The arrangement of landslides and subaerial rift zones on El Hierro indicates that growth of the submarine part of the edifice was not focussed within discrete narrow zones, but over a much broader area of flank. Offshore, the NW and NE extensions of the ridges are poorly defined, appearing to broaden towards the edifice base in water depths of ~3200 m. The Southern Ridge narrows offshore and has steeper, more gullied flanks. New sonar and seismic data allow the submarine flanks of El Hierro to be examined in detail, and appear to show that the best developed, Southern Ridge of El Hierro could in fact be the remnant of a deeply eroded edifice which may pre-date El Hierro itself.

2. Geological background

The Canary Islands are a group of seven major volcanic islands extending for 450 km from the northwest African continental margin (Fig. 1). The islands are Neogene in age (Schmincke, 1982; Arana and Ortiz, 1991), and are believed to have formed as the African plate moved over a mantle hotspot. A hotspot origin is suggested by a general east to west age progression of the island main shield building phases, ranging from >20 Ma in Fuerteventura in the east to <2 Ma in El Hierro and La Palma in the west (Carracedo et al., 1998). All the major islands, apart from La Gomera, have shown signs of volcanic activity during the last 5000 years (Schmincke, 1982).

El Hierro is the most southwesterly and youngest of the Canary Islands, with the oldest subaerial rocks dated at 1.12 Ma (Guillou et al., 1996). It has an estimated volume of 5500 km^3 (Schmincke, 1994) and rises from a base at 4000 m depth to an altitude of 1500 m above sea level. On the basis of studies of seafloor spreading magnetic anomalies, El Hierro is believed to be located on 156 Ma oceanic crust (Roeser, 1982; Roest et al., 1992).

The subaerial geology suggests that El Hierro grew during three main eruptive periods, with lavas erupted from rift zones during the last 37 ka covering much of the island (Guillou et al., 1996; Carracedo et al., 1997). Tightly aligned dyke complexes have surface expressions in the form of clusters of cinder cones that collectively form steep topographic ridges, interpreted as VRZs (Fuster et al., 1993; Carracedo, 1994). Guillou et al. (1996) note that El Hierro has the "greatest concentration of recent, well-preserved

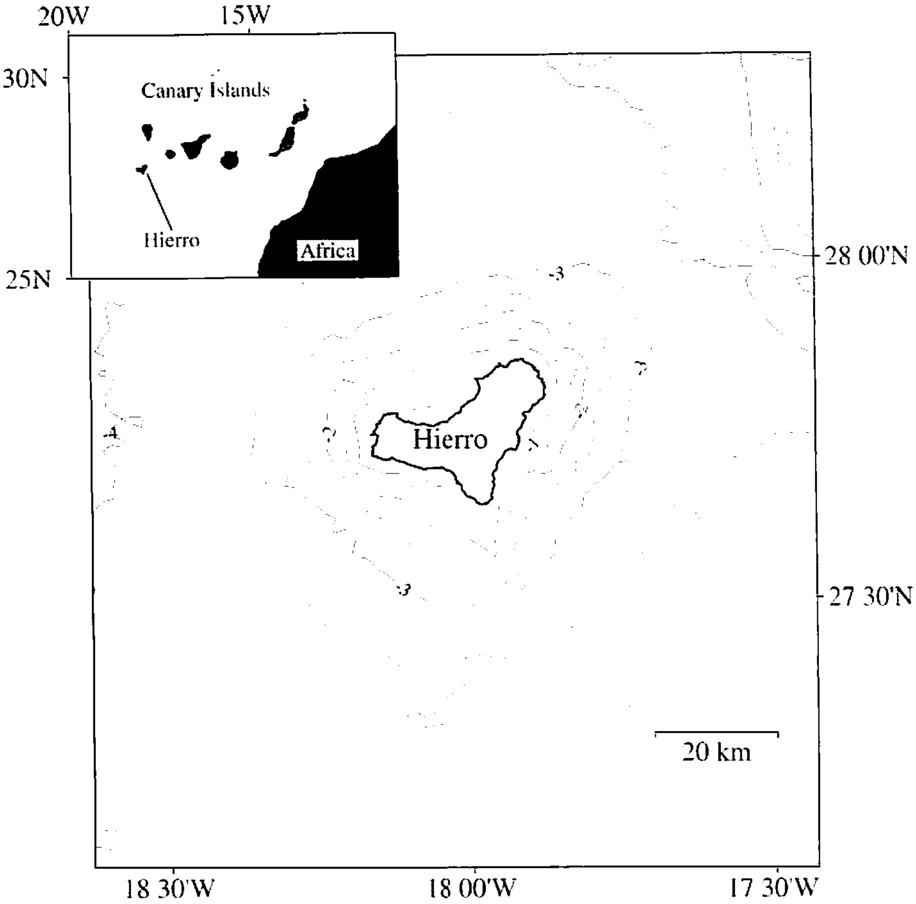


Fig. 1. Location map showing the island of El Hierro on the NW African margin. Simple bathymetry is shown, with contours at every 500 m.

emission vents in the Canarian Archipelago". The most recent volcanic eruption on El Hierro occurred in 1793 within the northwestern rift zone (Hernandez-Pacheco, 1982).

A three-armed shape is enhanced by large scale landsliding, since landslides, creating deep embayments, occur preferentially between the rift zones (Watts and Masson, 1995; Masson, 1996; Teide Group et al., 1997; Urgeles et al., 1997, 1999; Masson et al., 2000). The El Golfo failure on the northwest flank of El Hierro appears to be the most recent large landslide in the Canary Islands, occurring approximately 15 ka ago (Masson, 1996).

The following sections describe observations relating to constructional processes and considers the morphology and relative age of the anomalously long Southern Ridge compared to the NW and NE ridges of El Hierro.

3. Data processing and acquisition

In 1997, the Charles Darwin cruise CD108 obtained Simrad EM12 multibeam sonar and seismic data from the flanks of the western Canary Islands.

The Simrad EM12 multibeam sonar system is a full ocean depth echo sounder capable of recording highly detailed images of the seafloor bathymetry with an accuracy typically less than five metres in the vertical direction (Hammerstad et al., 1991). Depth values were processed using a 185-m gridding interval. Seismic reflection profiling was carried out using a

200-m-long, four-channel streamer and a single 300 in^3 BOLT 1500c airgun. Processing of the raw seismic data carried out using PROMAX Version 6.0 included deconvolution, stacking, amplitude recovery, bandpass filtering, migration and trace mixing. Significant improvements in the data were noted as a result of deconvolution.

Here we present data from the submarine flanks of El Hierro, Southern Ridge and seafloor adjacent to El Hierro. Topography (200 m contours) was digitised from a Spanish 'Instituto Geographico Nacional' map with some hydrographic data (200, 500 and 1000 m contours) for water depths down to 1000 m. Swath bathymetry data extend from a depth of about 1000 m oceanwards. A bathymetric and topographic grid was constructed from the data using GMT software (Wessel and Smith, 1991) using a gridding interval of 0.1 × 0.1 min of latitude and longitude.

4. Description of the morphology

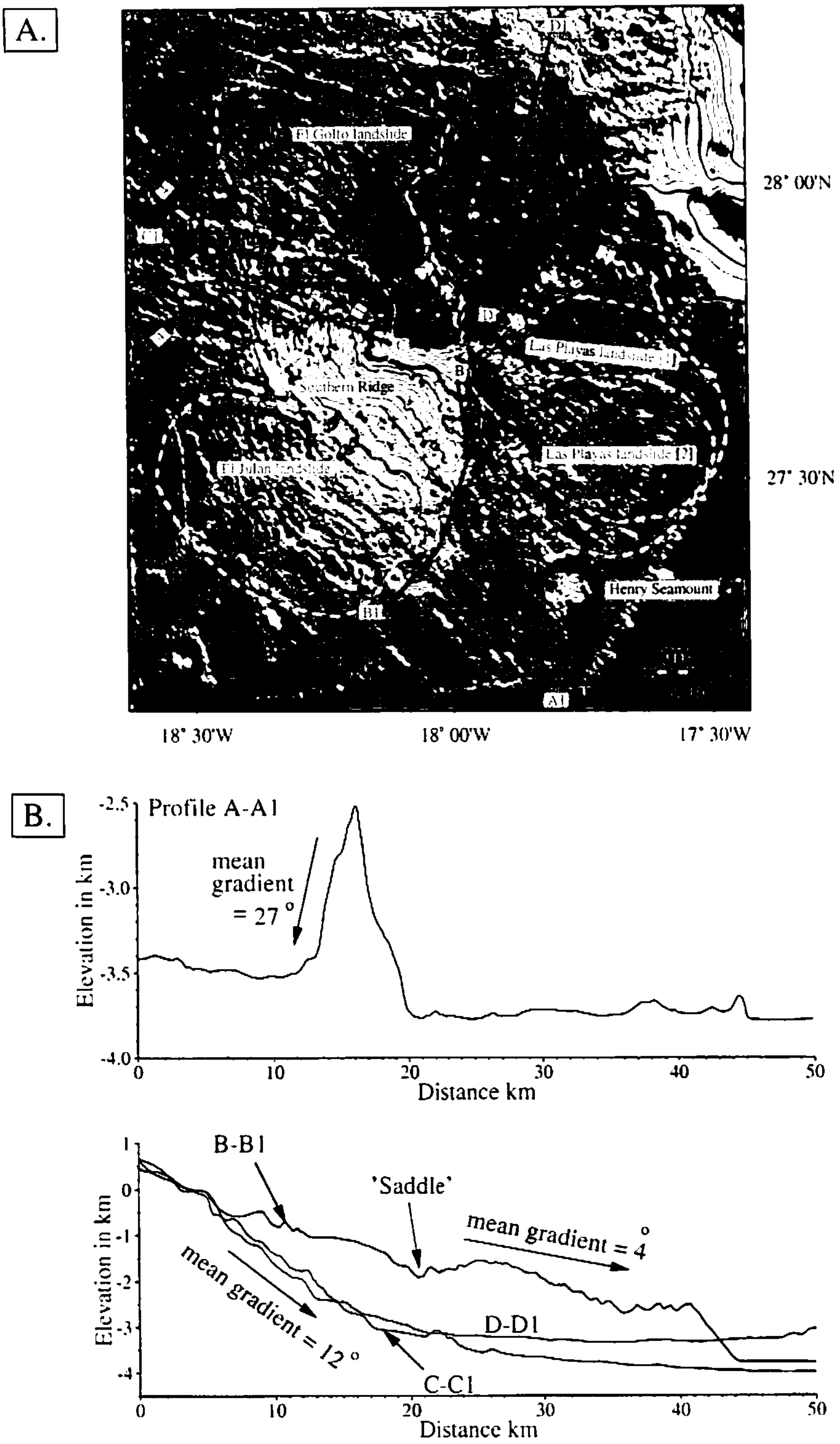
The study area covers all the submarine flanks of El Hierro, and includes the offshore extensions of the NW, NE and Southern Ridges, the giant landslides of El Golfo, Las Playas and El Julan and the 660-m-high 'Henry' seamount (Fig. 2) (Holcomb and Searle, 1991; Gee et al., 2000).

The NW and NE submarine ridges extend 20 km from the NW and NE onshore ridge systems, to a depth of ~3200 m. They have a highly irregular morphology characterised by numerous pinnacles and some irregular ridges and gullies. These ridges and gullies have an amplitude of a few hundred metres and a wavelength of a few kilometres (Fig. 2). Pinnacles are typically 2–4 km across and 150 m high, sometimes elongated or aligned downslope in groups of two or three, suggesting that they could be related to dyke activity radiating from a central volcanic zone. They are concentrated on the NW and NE submarine ridges but a few can also be observed within the El Julan and Las Playas landslide valleys (Fig. 3). There are no pinnacles within the El Golfo landslide valley and south of 27° 30′N on the Southern Ridge. Below 2 km within the NW and NE ridges are a series of lobate features with 100–500-m-high steep-fronts and gently dipping tops (Fig. 3). These are interpreted as lobes of ponded lava, based on their similarity with features described from Hawaiian submarine rift zones (Moore and Chadwick, 1995). This irregular morphology of ridges, gullies, pinnacles and deep lobate features extends over broad areas between the three giant landslides and is interpreted as constructional, unfailed island flank.

Mean gradients along axis for the NE and NW submarine ridges are 12° but locally exceed 30° (Fig. 2). There is a clear break-of-slope at around 3200 m, which marks the base of the edifice. Here, the slope angles decrease to less than 1° over relatively smoothly sedimented seafloor (Figs. 2B and 3). The landslide regions of El Golfo, Las Playas and El Julan between the three ridges have a much smoother morphology than the ridges and gentler slope angles, in the region of 5–15° (Fig. 2). Landslides of El Hierro are the subject of a separate paper and not discussed at length here (Gee et al., 2000).

The Southern Ridge extends for 38 km from the coast, and reaches an elevation of 2000 m, south of 27°30′N, above the surrounding seafloor at its highest point. It is a narrow structure that curves gently to the southwest, with steep flanks rising to a narrow crest. The ridge narrows from approximately 20 km close to shore to less than 10 km at its tip. The base of the ridge is defined by the 3700 m contour on its southern and southeastern flanks. This divides the steep, rugged flanks of the Southern Ridge from smooth, almost flat sedimented seafloor. The seafloor on the western side of the Southern Ridge is elevated by around 300 m and is slightly more rugged, reflecting the morphology of the El Julan debris avalanche (Holcomb and Searle, 1991; Gee et al., 2000). To the south of 27°30′N, no arcuate headwall scars or areas of

Fig. 2. (A) Grey-shaded bathymetry and topography of El Hierro with km contours annotated. Submarine landslides are outlined with white dashed lines and the locations of four profiles (B) constructed from the data are shown with thick black lines. (B) Profile A-A1 samples bathymetry across the Southern Ridge along the same track as the seismic reflection profile shown in Fig. 5. Note the elevation difference of ~300 m between seafloor on the east and west of the Ridge. Profiles B-B1, C-C1 and D-D1 compare the NE, NW and Southern Ridges. Note the more gentle gradient and a prominent 'saddle' in the profile of the Southern Ridge (B-B1).


A.
El Golfo landslide
Las Playas landslide [1]
Las Playas landslide [2]
El Julan landslide
Southern Ridge
Henry Seamount
D1
C1
D
C
B
B1
A1
28° 00'N
27° 30'N
18° 30'W
18° 00'W
17° 30'W
B.
Profile A-A1
mean gradient = 27°
Elevation in km
-2.5
-3.0
-3.5
-4.0
Distance km
0
10
20
30
40
50
B-B1
'Saddle'
mean gradient = 4°
mean gradient = 12°
D-D1
C-C1
Elevation in km
1
0
-1
-2
-3
-4
Distance km
0
10
20
30
40
50

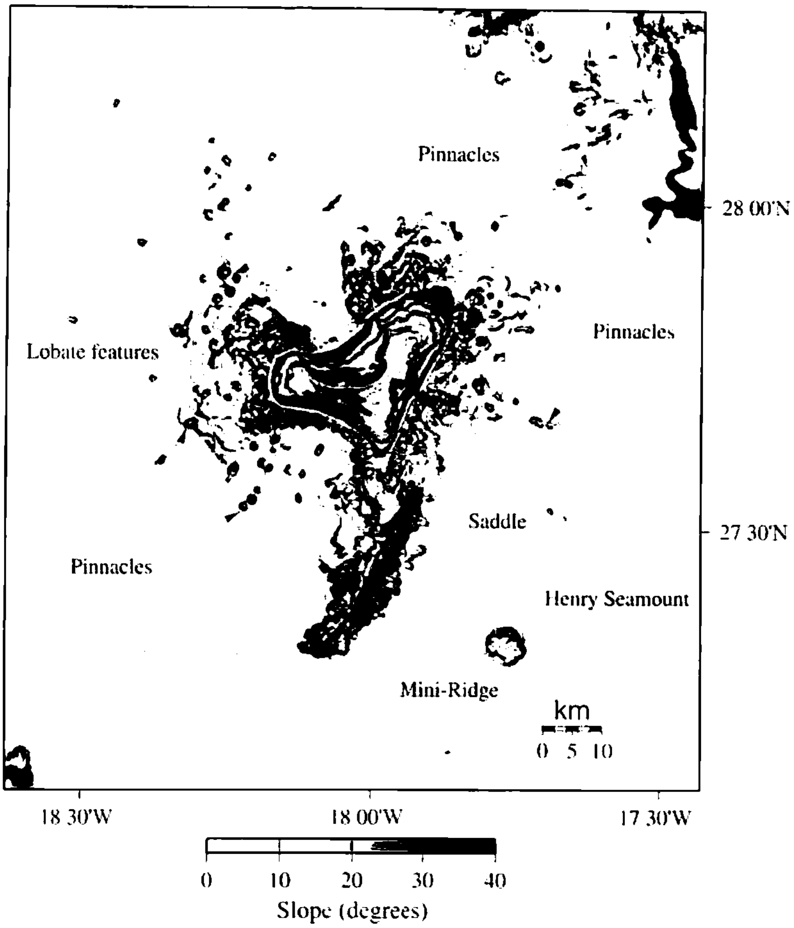


Fig. 3. Bathymetry and topography of El Hierro. Shades of grey correspond to slope angle.

subdued morphology, which might indicate landsliding can be recognised. The acute break-of-slope at ~3700 m contrasts with the debris avalanches which decline gradually in slope (Gee, 1999). Some parts of the Southern Ridge north of 27°30′N, however, may have been affected by landsliding, although the exact boundaries are unclear.

A prominent 400 m saddle divides the Southern Ridge (Fig. 2B) near 27°30′N, 17°58′W. This saddle divides two very distinct morphologies. South of 27°30′N, the flank morphology is characterised by downslope aligned ridges and gullies. These 'ridges and gullies' are best developed on the eastern side of the ridge and have a mean wavelength of 1.5 km and a mean amplitude of 75 m (Figs. 3 and 4). This morphology contrasts strongly with other areas of flank on El Hierro. Ridges and gullies are observed on the NE and NW ridges; however, these are larger and significantly more irregular (see above). Immediately north of 27°30′N mean flank slopes are around 20° or less and the morphology is significantly more subdued. Here, there are fewer ridges and gullies and a less well-defined break-of-slope, best observed along the eastern flank of the Southern Ridge (Fig. 4).

Mean flank gradients of the Southern Ridge south of 27°30′N are 27°, locally reaching >40° (Fig. 2B). The flanks rise to a narrow crest characterised by a narrow band of low gradient only 500 m wide with steep margins (Figs. 3 and 4), which speculatively could be the remnant of eroded dyke swarms within the Ridge. The mean slope along the whole ridge crest is only 4°, which contrasts with a mean gradient of 12°

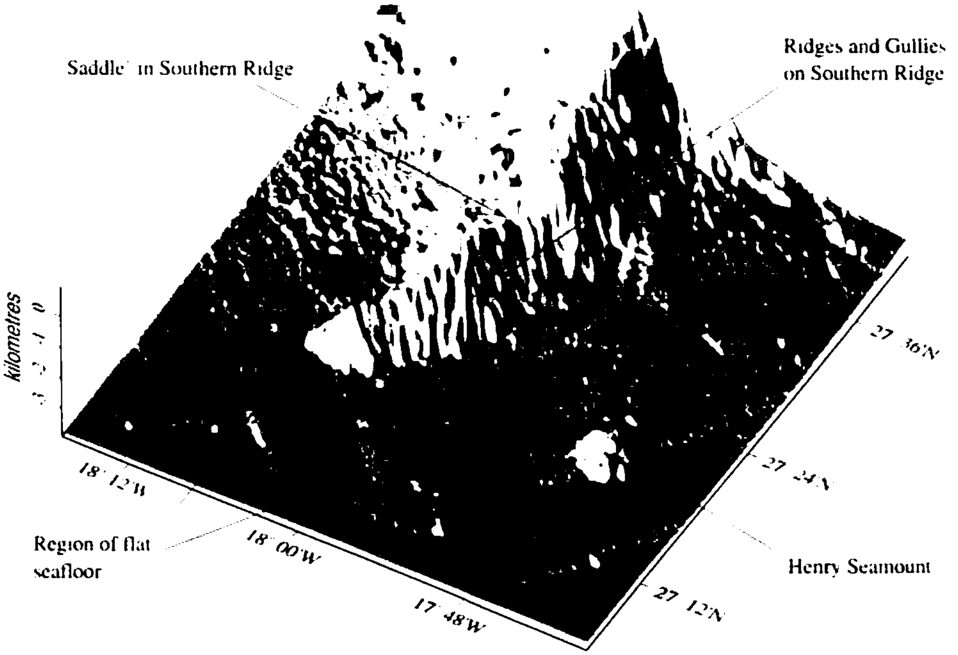


Fig. 4. Grey-shade image of the Southern Ridge derived from bathymetry data. Note the well-developed system of gullies on the southeastern flank of the Southern Ridge.

for the NW and NE ridges. The tip of the Southern Ridge forms a steep slope (>30°) over 1 km high with a sharp break-of-slope at 3700 m, where the ridge meets the smoothly sedimented seafloor (Fig. 2B).

A 10-km-wide, 660-m-high seamount, hereafter called the 'Henry Seamount', which is approximately circular in plan view, is seen to the south east of the ridge, near 27°20'N, 17°17'W. It is dome-shaped with slopes that steepen to 20° nearer its base, where there is a sharp break-of-slope with the surrounding seafloor. EM12 multibeam data show that this seamount is characterised by low backscatter, indicating that it is covered with at least several metres of sediment (Mitchell, 1993). A subdued morphology of gullies and ridges can be observed radiating from its centre.

Directly to the south of the Southern Ridge, the seafloor is relatively featureless, characterised by very small gradients (Fig. 4). To the northeast and, especially, west of the Ridge the seafloor has a gently stepped morphology, where extensive landslide deposits have been mapped (Holcomb and Searle, 1991; Gee et al., 2000).

5. Interpretation of seismic data

On the steep flanks of the ridge, no internal structures are imaged. The chaotic internal structure of the El Julan debris avalanche west of the Southern Ridge, and more stratified sediments over rugged acoustic basement to the east, are shown by seismic profiles (Fig. 5). To the west of the Ridge the seismic data consists of short, often steeply dipping irregular reflectors. This is a typical seismic record over debris avalanche deposits (Lipman et al., 1988), reflecting the blocky nature of the deposit. The ridge appears to have restricted deposition of debris avalanche deposits spreading from the El Julan landslide. This indicates that the ridge must be at least as old as the El Julan landslide, which is dated >200 ka (Gee, 1999).

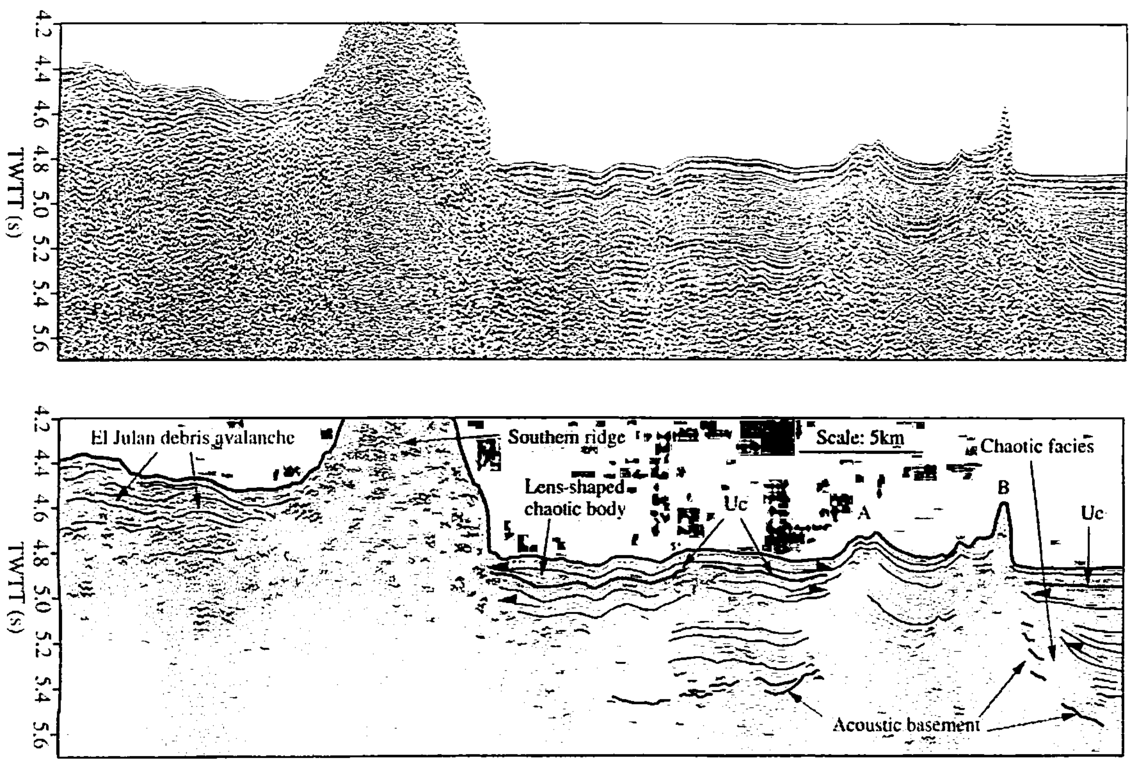


Fig. 5. Interpreted seismic reflection section showing the Southern Ridge and structure of the adjacent sediments. TWTT = two-way travel time. Penetration over the Southern Ridge is zero. To the east, ~0.6 s (TWTT) of stratified seismic facies overly acoustic basement at ~5.4 s (TWTT). To the west, a chaotic seismic facies, interpreted as debris avalanche, is shown. Apparent onlap is shown as black half arrows. An unconformity (Uc) interpreted as relating to the early growth stage of El Hierro is seen at ~0.1 s (TWTT). An acoustic basement high is shown at A and an outcrop at B.

On the eastern side of the ridge up to 0.7 s (TWTT) of weakly folded, stratified sediments are recorded over acoustic basement. Subsurface reflectors here appear to onlap the eastern flank of the Southern Ridge and onlap/drape basement structures adjacent to the ridge (Fig. 5). This is interpreted as evidence that stratified sediments post-date the ridge. High amplitude reflectors above a major unconformity at about 0.1 s (TWTT) below seafloor are believed to record the early growth and initial masswasting of El Hierro around 1 Ma ago (Urgeles et al., 1997; Gee, 1999). When viewed on a larger scale, the stratified facies is restricted to a small area south and southeast of the Southern Ridge. Here, seismic (Fig. 5) and EM12 multibeam (Fig. 2) data indicate no significant landslides have been deposited at least since the Late Miocene (Gee, 1999).

In combination, the onlapping reflectors, lack of large-scale landslide deposits to the east and the restriction of the El Julan debris avalanche to the west are the main seismic evidence that the Southern Ridge is older than the El Julan landslide.

6. Discussion

6.1. Contrasts between submarine ridges on El Hierro

The broad areas of irregular submarine morphology described on the NW and NE flanks contrast strongly with the narrow, discrete Southern Ridge south of 27°30′N. The NW and NE flanks have similar gradients and morphological features indicating they might both have a similar age and origin, although we have no other data to substantiate this. The broad, irregular morphology that characterises these two ridges

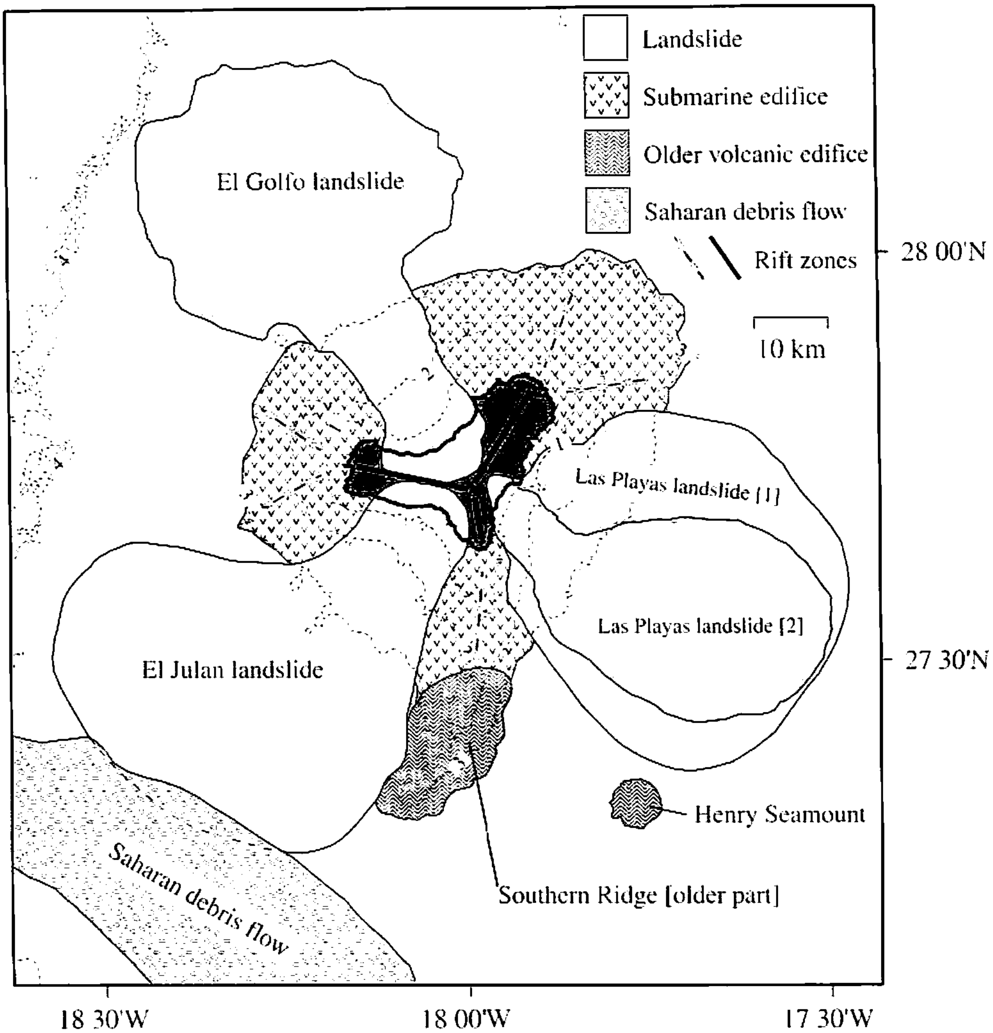


Fig. 6. Morphological interpretation of El Hierro and surrounding submarine flanks based on seismic, sonar, bathymetry and topography data. Contours are annotated every km. South of 27°30′N the Southern Ridge and Henry Seamount are shown as separate, older, volcanic edifices. Flank types interpreted as constructive rift-zones relating to the El Hierro edifice are illustrated as 'submarine edifice' (see key). Onshore rift zones are taken from previously published geological mapping (thick black lines). Interpreted locations of offshore rift zones are shown as thick, grey-dashed lines. Note the inferred 'bifurcation' of both the NE and NW offshore rift zones.

suggests either a wide area of constructional dyke activity, or a bifurcation of the onshore rift zones seaward (Fig. 6).

The Southern Ridge has a very different character south of 27°30′N, which suggests it has a different age and origin (Fig. 6). One of the most distinct features of this part of the Southern Ridge is its heavily gullied erosional morphology. Similar long linear gullies or chutes, interpreted as actively transporting material, were reported on the northern flank of Stromboli (Kidd et al., 1998). The absence of such well-developed gullies elsewhere on El Hierro suggests a greater age for the Southern Ridge. The absence of constructional pinnacles (which are common over much of the submarine flank regions) may reflect the volcanic stability of the Ridge, allowing erosional processes to remove any such features that might have existed and exposing a core complex of more resistant dyke material. A lack of talus, or mass-wasting products at the base of the slope also indicates that no significant erosion has occurred in recent times.

A similar "gullied" morphology was described from the northern flank of the Anaga edifice on Tenerife by Watts and Masson (1995). They describe a "rough topography, composed of ridges and valleys with characteristic peak to trough amplitudes of 100–300 m and wavelengths of 2–3 km". The subaerial island flanks are characterised by narrow valleys known locally as "barrancos", the development of which can be a relative indicator of age. For example, on the older volcanic edifices such as Anaga, Teno and Gomera, the "barrancos" are well developed. Although barrancos are cut by fluvial erosion while submarine gullies are probably eroded by turbidity currents, both arguably provide a relative indication of age.

6.2. *The Southern Ridge longitudinal profile*

Field observations indicate that flank rift zones are composed of extensive dyke swarms radiating from a central magma chamber (Fiske and Jackson, 1972; Pollard et al., 1983; Knight and Walker, 1988). Studies of rift zones on Hawaii indicate that the along axis profiles of flank rift zones have fairly uniform topographic slopes of just a few degrees which progressively deepen underwater (Fialko and Rubin, 1999). They argued that dykes intruding the flanks to form rift zones were driven by excess magma pressure in the dyke and would naturally evolve to a critical slope. The long profile of the Southern Ridge is far from uniform and although its mean along axis slope is only 4°, slopes are >20° in places, which contrast with Hawaiian rift zones. Along the East Rift Zone of Kilauea volcano, Hawaii (the Puna Ridge), along-axis slopes of ~2.9° were measured (Lonsdale, 1989). Compared with the Puna Ridge, the Southern Ridge has a higher mean along axis slope. In modelling of dyke flow driven by excess magma chamber pressure, Fialko and Rubin (1999) showed how VRZs might evolve a critical overall slope. The implication of a 400 m saddle in the Southern Ridge is that it was probably not formed by magma propagating down-rift from a central magma chamber. However, the morphology data imply that the Southern Ridge north of 27°30′N might be a flank rift zone, which connects with the main El Hierro edifice.

6.3. *Comparison with other flank rift zones*

The Cumbre Vieja ridge on Las Palmas Island is an active rift zone, characterised by fast growth, steep flanks (>30°) and along strike orientated faults related to recent volcanism (Carracedo, 1994). Offshore, the Cumbre Vieja ridge also is characterised by a saddle, implying that it too is not a continuous feature. However, the offshore section of the Cumbre Vieja ridge is broader and characterised by a low relief plateau and a flank embayment on the southwest margin.

Tenerife is the other Canarian Island to be characterised by a three-armed ridge morphology. Local Bouguer gravity anomalies clearly show a three-armed pattern, which matches the island's three ridges (MacFarlane and Ridley, 1968). The northeastern ridge of Tenerife is steep-sided and long, compared with the other two ridges (Carracedo, 1994). The present island of Tenerife clearly has a more complex history than El Hierro, comprising the older massifs of Anaga, Teno and Roque del Conde, plus more recent volcanics associated with Las Canadas and the present Teide strato volcano (Ancochea et al., 1990). This makes comparison difficult, although none of the ridges extend offshore as narrow, steep-sided structures.

The seamount of Loihi is considered to be the most recent volcanic construction of the hotspot that underlies the southern flank of Hawaii (Klein, 1981; Moore et al., 1982; Malahoff, 1987). Loihi is an elongate seamount (33 × 22 km) with a central region of low summit relief and pit craters (Fornari et al., 1984). Similar to the Southern Ridge of El Hierro, the rift arms of Loihi are narrow and steep sided. Loihi differs by having flank embayments and more gentle lower flank gradients, which indicates mass wasting. An actively propagating rift system would itself be prone to flank collapse, as seen around the young Loihi seamount south of Hawaii (Moore et al., 1994). However, the lack of embayments, related deposits and general base-of-slope talus suggest that the Southern Ridge is stable.

6.4. *A comment on flank regeneration rates*

Subaerial geological data indicate that Island growth was concentrated along three well-defined ridges (Fuster et al., 1993). However, the interpreted presence of constructional volcanic pinnacles within the El Julan and Las Playas landslide valleys (Fig. 3) are evidence for off-rift volcanic activity. Given that the age of the El Julan landslide was estimated at >200 ka (Gee, 1999) an estimate of the volume of flank regeneration can be made, based on the volume of volcanic material produced since the flank was "reset" by landsliding erosion. For calculation purposes, each "pinnacle" was assumed to be cone shaped measuring 3 km across its basal diameter and 150 m high. This indicates a flank regeneration volume of 20 km^3 within the El julan landslide valley. This calculation does not take into account the volcanic "pinnacle" roots that might be within the landslide deposit, and so is a minimum volume estimate. However, this low flank regeneration volume reflects the fact that most edifice growth occurred in the submarine shield building phase and that in at least the last 200 thousand years the inter-rift flank growth rate has been very slow.

6.5. Surrounding seafloor structure and the Henry Seamount

We speculate that the gentle folding of the strata shown on the seismic profile (A-A1, Fig. 5) might have been caused when the Southern Ridge was active, prior to the rapid growth of El Hierro to the north. It is likely that some of the observed subsurface geometries are caused by intrusion of magmatic sills from the ridge during the time of active growth, over which sediments have subsequently been draped, resulting in differential compaction and hence apparent folding. Another likely source for the sills is the El Hierro edifice to the north.

The Henry Seamount (Fig. 3) appears to be linked to an acoustic basement high observed on seismic data (features 'A' and 'B', Fig. 5). In the absence of more accurate dating information, a sediment drape of several metres could indicate an age of a few hundred thousand years. In addition, absence of landslide scars or related deposits indicates a relatively stable seamount. This we interpret as evidence that the seamount has a similar age to that of the Southern Ridge (Fig. 5).

6.6. The age of the Southern Ridge

The restriction of the El Julan landslide to the western side of the Southern Ridge indicates the minimum height and age of the Southern Ridge before landslide emplacement. The El Julan landslide has a maximum thickness estimated at 300 m and age >200 ka (Gee, 1999), therefore placing a constraint on the minimum height and age of the ridge at the time of landslide emplacement. While the restriction of landslide deposits to the west indicates the presence of a morphological barrier at least 300 m high as recently as 200 ka, we speculate that the ridge may be older (Fig. 6). The lack of landslide deposits directly to the south and east of the Southern Ridge is also curious, as mass wasting products appear to cover most the remaining flanks of El Hierro at similar water depths. We speculate that the small area of smooth seafloor to the south of the Southern Ridge was possibly shielded from debris avalanche flows from the actively growing flanks of El Hierro by the presence of the older and inactive Southern Ridge.

7. Summary

The Southern Ridge is interpreted as being at least as old as the El Julan landslide. The Southern Ridge which was at least 300 m high at the time of the El Julan landslide, predates the El Julan debris avalanche (>200 ka) and Las Playas landslides (145–176 ka), although it is not clear by how long. The distinct gullied morphology of the Southern Ridge reflects the dominance of erosional processes on a relatively old and stable volcanic edifice. This contrasts with the rapid constructive and destructive processes, which have produced the 5-km-high El Hierro edifice to the north in 1.12 Ma. Is there a Southern Rift zone? Our interpretation is that the part of the Southern Ridge south of 27°30′N is an older edifice, not part of a southern propagating rift zone from El Hierro. However, the subaerial geology indicates the presence of a recently active southern rift zone (Fuster et al., 1993). The general characteristics, i.e. morphology and geometry, of the Southern Ridge extending as far as 27°30′N are broadly similar to those of the NW and NE rift zones, although we do not have sufficient data at present to say more.

Acknowledgements

We would like to thank the Captain, officers and crew of the RRS *Charles Darwin* CD108 for their invaluable help in acquiring the data. Thanks to Marco Ligi for advice concerning seismic processing. M.J.R. Gee gratefully acknowledges NERC studentship GT4/95/252 and the research facilities at Earth Sciences, Oxford University and Southampton Oceanography Centre. Figures for this paper were prepared with GMT software (Wessel and Smith, 1991) and PROMAX Version 6.0. N.C.M. was supported by a Royal Society University Research Fellowship.

References

Ancochea, E., Fuster, J.M., Ibarrola, E., Cendrero, A., Coello, J., Hernan, F., Cantagrel, J.M., Jamond, C., 1990. Volcanic evolution of the island of Tenerife (Canary Islands) in the light of new K–Ar data. J. Volcanol. Geotherm. Res. 44, 231–249.

1991. The Canary Islands: tectonics, magmatism and geodynamic framework. In: Arana, V., Ortiz, R. (Eds.), Magmatism in Extensional Structural Settings. Springer, Berlin, pp. 209–249.

Carracedo, J.C., 1994. The Canary Islands: an example of structural control on the growth of large oceanic-island volcanoes. J. Volcanol. Geotherm. Res. 60, 225–241.

Carracedo, J.C., 1996. A simple model for the genesis of large gravitational landslide hazards in the Canary Islands. In: McGuire, W.J., Jones, A.P., Neuberg, J. (Eds.), Volcano Instability on the Earth and Other Planets. Geol. Soc. London, Spec. Publ. 110, 125–135.

Carracedo, J.C., Day, S., Guillou, H., Rodriguez Badiola, E., Canas, J.A., Perez Torrado, F.J., 1998. Hotspot volcanism close to a passive continental margin: the Canary Islands. Geol. Mag. 135, 591–604.

Carracedo, J.C., Day, S., Guillou, H., Torrado, F.J.P., 1997. El Hierro Geological Excursion Handbook. Estacion Volcanologica de Canarias and the Universidad de Las Palmas, Tenerife/Gran Canaria, 43 pp.

Delaney, P.T., Fiske, R.S., Miklius, A., Okamura, A.T., Sako, M.K., 1990. Deep magma body beneath the summit and rift zones of Kilauea volcano, Hawaii. Science 247, 1311–1316.

Elsworth, D., Voight, B., 1995. Dike intrusion as a trigger for large earthquakes and the failure of volcano flanks. J. Geophys. Res. 100, 6005–6024.

Fialko, Y.A., Rubin, A.M., 1999. What controls the along-strike slopes of volcanic rift zones?. J. Geophys. Res. 104, 20 007–20 020.

Fiske, R.S., Jackson, E.D., 1972. Orientation and growth of Hawaiian volcanic rifts: the effect of regional structure and gravitational stresses. Proc. R. Soc. London A329, 299–326.

Fornari, D.J., Ryan, W.B.F., Fox, P.J., 1984. The evolution of craters and calderas on young seamounts: insights from Sea MARC I and Sea Beam sonar surveys of a small seamount group near the axis of the East Pacific Rise at ~10°N. J. Geophys. Res. 89, 11069–11083.

Fuster, J.M., Hernan, F., Cendrero, A., Coello, J., Cantagrel, J.M., Ancochea, E., Ibarrola, E., 1993. Geochronologia de la Isla de El Hierro (Islas Canarias). Bol. R Soc. Esp. Hist. Nat. (Sec. Geol.) 88 (1–4), 85–97.

Gee, M.J.R., 1999. The collapse of oceanic islands and the mechanics of long runout debris flows: examples from the NW African margin. DPhil thesis. University of Oxford.

Gee, M.J.R., Masson, D.G., Watts, A.B., 2000. Landslides and the evolution of El Hierro in the Canary Islands. Submitted for publication.

Guillou, H., Carracedo, J.C., Perez-Torrado, F., Rodriguez Badiola, E., 1996. K–Ar ages and magnetic stratigraphy of a hotspot-induced, fast-grown oceanic island: El Hierro, Canary Islands. J. Volcanol. Geotherm. Res. 73, 141–155.

Hammerstad, E., Pohner, F., Parthiot, F., Bennett, J., 1991. Field Testing of a new Deep Water Multibeam Echo Sounder. Oceans '91, pp. 743–749.

Hernandez-Pacheco, A., 1982. Sobre una posible erupcion en 1793 enla isla de El Hierro (Canarias). Est. Geol. 38, 15–25.

Holcomb, R.T., Searle, R.C., 1991. Large landslides from oceanic volcanoes. Mar. Geotechnol. 10, 19–32.

Kidd, R.B., Lucchi, R.G., Gee, M.J.R., Woodside, J.M., 1998. Sedimentary processes in the Stromboli Canyon and Marsili Basin, SE Tyrrhenian Sea: results from side-scan sonar surveys. Geo-Mar. Lett. 18, 165–171.

Klein, F.W., 1981. A linear gradient crustal model for south Hawaii. Bull. Seismol. Soc. Am. 71, 1503–1510.

Knight, M.D., Walker, G.P.L., 1988. Magma flow directions in dikes of the Koolau complex, Oahu, determined from magnetic fabric studies. J. Geophys. Res. 93, 4301–4319.

Labazuy, P., 1996. Recurrent landsliding events on the submarine flank of Piton de la Fournaise volcano (Reunion Island). In: McGuire, W.J., Jones, A.P., Neuberg, J. (Eds.), Volcano Instability on the Earth and Other Planets. Geological Society, London, pp. 295–306.

Lipman, P.W., Normark, W.R., Moore, J.G., Wilson, J.B., Gutmacher, C.E., 1988. The giant submarine Alika debris slide, Mauna Loa, Hawaii. J. Geophys. Res. 93 (B5), 4279–4299.

Lonsdale, P., 1989. A geomorphological reconnaissance of the submarine part of the East Rift Zone of Kilauea Volcano, Hawaii. Bull. Volcanol. 51, 123–144.

Macdonald, G.A., 1949. Petrography of the island of Hawaii. U.S. Geol. Surv. Prof. Pap. 214-D.

MacFarlane, D.J., Ridley, W.I., 1968. An interpretation of gravity data from Tenerife, Canary Islands. Earth Planet. Sci. Lett. 4, 481–486.

Malahoff, A., 1987. Geology of the summit of Loihi submarine volcano. In: Decker, R.W., Wright, T.L., Stauffer, P.H. (Eds.), Volcanism in Hawaii. U.S. Geol. Surv. Prof. Pap. 1350, 133–144.

Masson, D.G., 1996. Catastrophic collapse of the volcanic island of

Hierro 15 ka ago and the history of landslides in the Canary Islands. Geology 24, 231–234.

Masson, D.G., Watts, A.B., Gee, M.J.R., Urgeles, R., Mitchell, N.C., Le Bas, T.P., Canals, M., 2000. Slope failures on the flanks of the western Canary Islands. Submitted for publication.

Mitchell, N.C., 1993. A model for attenuation of backscatter due to sediment accumulations and its application to determine sediment thickness with GLORIA sidescan sonar. J. Geophys. Res. 98, 22477–22493.

Mitchell, N.C., 1998. Characterising the irregular coastlines of volcanic ocean islands. Geomorphology 23, 1–14.

Moore, J.G., Chadwick, W.W., 1995. Offshore geology of Mauna Loa and adjacent areas, Hawaii. Mauna Loa Revealed: Structure, Composition, History and Hazards. American Geophysical Union.

Moore, J.G., Clague, D.A., Holcomb, R.T., Lipman, P.W., Normark, W.R., Torresan, M.E., 1989. Prodigious submarine landslides on the Hawaiian Ridge. J. Geophys. Res. 94, 17465–17484.

Moore, J.G., Clague, D.A., Normark, W.R., 1982. Diverse basalt types from Loihi seamount, Hawaii. Geology 10, 88–92.

Moore, J.G., Normark, W.R., Holcomb, R.T., 1994. Giant Hawaiian landslides. Annu. Rev. Earth Planet. Sci. 22, 119–144.

Ollier, G., Cochonat, P., Lenat, J.F., Labazuy, P., 1998. Deep-sea volcaniclastic sedimentary systems: an example from La Fournaise volcano, Reunion Island, Indian Ocean. Sedimentology 45, 293–330.

Pollard, D.D., Delaney, W.A., Duffield, E.T., Endo, A.T.O., 1983. Surface deformation in volcanic rift zones. Tectonophysics 94, 541–584.

Roeser, H.A., 1982. Magnetic anomalies in the magnetic quiet zone off Morocco. In: Geology of the Northwest African Continental Margin. Springer, Berlin, pp. 61–68.

Roest, W.R., Danobeitia, J.J., Verhoef, J., Collette, B.J., 1992. Magnetic anomalies in the Canary Basin and the Mesosoic Evolution of the central North Atlantic Marine. Geophys. Res. 14, 1–24.

Schmincke, H.U., 1982. Geology of the northwest African continental margin. Volcanic and Chemical Evolution of the Canary Islands. Springer, Berlin pp. 273–308.

Schmincke, H.U., 1994. Geological Field Guide of Gran Canaria, Pluto Press, Kiel, Germany, 219 pp.

Teide_Group, Palomo, C., Acosta, J., Sanz, J.L., Herranz, P., Munoz, A., Uchupi, E., Escartin, J., 1997. Morphometric interpretation of the northwest and southeast slopes of Tenerife, Canary Islands. J. Geophys. Res. 102, 20325–20342.

Urgeles, R., Canals, M., Baraza, J., Alonso, B., Masson, D.G., 1997. The most recent megaslides on the Canary Islands: the El Golfo Debris Avalanche and the Canary Debris Flow, west El Hierro Island. J. Geophys. Res. 102, 20305–20323.

Urgeles, R., Masson, D.G., Canals, M., Watts, A.B., Le Bas, T., 1999. Recurrent large-scale landsliding on the west flank of La Palma, Canary Islands. J. Geophys. Res. 104, 25331–25348.

Vogt, P.R., Smoot, N.C., 1984. The Geisha Guyots: multi-beam bathymetry and morphometric interpretation. J. Geophys. Res. 89, 11085–11107.

Watts, A.B., Masson, D.G., 1995. A giant landslide on the north flank of Tenerife, Canary Islands. J. Geophys. Res. 100, 24499–24507.

Wessel, P., Smith, W.H.F., 1991. Free software helps map and display data. EOS Trans. AGU 72, 441.